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The goal of the research is to achieve interferometric phase measurements below the standard quantum limit, the shot noise limit, by using squeezed quantum states of light. The squeezing is accomplished in single-mode polarizations maintaining optical fibers. Using fiber components, the light thus squeezed can be injected with minimum loss into fiber interferometers (such as a fiber gyro).

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Annual Report

Interferometric Measurement
Grant N00014-92-J-1302

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Staff: S. Namiki, visiting scientist
L. Boivin, C. Yu, graduate students

The goal of the research is to achieve interferometric phase measurements below the standard quantum limit, the shot noise limit, by using squeezed quantum states of light. The squeezing is accomplished in single-mode polarizations maintaining optical fibers. Using fiber components, the light thus squeezed can be injected with minimum loss into fiber interferometers (such as a fiber gyro).

Low Noise Fiber Sources

The successful experiments of K. Bergman that resulted in operation 5.1dB below shot noise were carried out with a specially designed mode-locked Nd:YLF laser at 1.3μm. The laser was diode pumped and extremely stable. Experiments with soliton squeezing both at IBM and at MIT used the coupled cavity F-center laser at 1.5μm and did not achieve noise reduction below shot noise better than 2.1dB. We believe that the fluctuations of this laser source were responsible for the low amount of noise reduction. We intend to experiment again with soliton squeezing, however, with sources of lower fluctuation levels. For this purpose we are actively pursuing the study of noise in mode-locked fiber ring soliton lasers. The fiber rings can be constructed with no air-gaps, thus providing a very stable environment for the laser radiation. Measurements of the timing jitter of the modelocked pulses and theory developed for this purpose revealed that the sole source of noise of timing jitter is the amplified spontaneous emission[1]. The timing jitter observed with a 0.1s integration time was lower than ever previously reported. The amplitude fluctuations were also very low (0.2%). We expect that mode-locked fiber ring lasers, maybe with post-amplification, will serve as the ideal source for squeezing experiments with solitons.

In order to obtain a better understanding of soliton squeezing, we have calculated the degree of squeezing of solitons without using the small quantum noise approximation. This analysis, based on the exact time dependence of the Bethe eigenstates for the quantized

nonlinear Schrödinger equation confirms the results of the linearized theory and establishes its domain of validity[2].

50/50 Couplers

One of the critical elements in fiber squeezing experiments in a Sagnac loop is the fiber coupler. Deviation from the perfect splitting ratio can affect the noise reduction adversely. The splitting ratio is wavelength dependent. Even if the splitting ratio is 50/50 at one frequency within the pulse spectrum, it may deviate at other frequencies. This may affect adversely the squeezing of short pulses. The frequency dependent splitting ratio leads to the splitting of the incident pulse into two pulses of slightly different carrier frequency. Due to the group velocity dispersion, the pulses return to the beam splitter slightly displaced in time and do not interfere perfectly.

This is the reason that we have investigated means of fabricating beam splitters that maintain balance over bandwidths of 100fs pulses. The work is done in conjunction with the Nanostructures Laboratory. Dr. Brent Little, a postdoc working on integrated optical waveguide projects, has arrived at a novel design that permits the compensation of the frequency dependence of the coupling coefficent of coupled waveguides. We expect that this new development will also be of importance in the general field of waveguide optics.

Raman Noise

In squeezing experiments with solitons it is advantageous to use short pulses to maximize the nonlinear Kerr phase shift. However, as shorter and shorter pulses are used, adverse effects may show up. We have mentioned the frequency dependence of the coupling ratio of the input Sagnac loop coupler as one such effect. Another effect is the Raman gain. Raman gain calls for the introduction of a noise source. This is true even if the pulse itself acts as the pump, with photons at higher frequencies being replaced by photons of lower frequencies. We have analyzed this Raman gain consistent with quantum mechanics, using a model of coupling to vibrational modes[3]. The model gives rise automatically to noise sources that assure commutator conservation required for a selfconsistent theory. The impact of Raman noise on short pulse squeezing was analyzed. It was found that squeezing with pulses longer than 100fs is not seriously affected by Raman noise.

Squeezing without a Sagnac Loop

We proposed a new method to generate squeezed light using an optical fiber not closed in a loop[4]. The pump of one polarization squeezes the vacuum in the other polarization

via cross-phase modulation. The separation of pump and squeezed vacuum is effected by a polarization sensitive beam splitter. The system is much simpler than the Sagnac loop configuration. In the future, we plan to carry out experiments on such a system.

Positive Dispersion

Thus far, all squeezing experiments have been done either at zero dispersion, or at negative dispersion with solitons. Soliton squeezing has the advantage, at least in theory, that the pulse is squeezed as a whole and detected as a whole, so that the phases of the squeezed radiation and of the pump are uniform across the pulse profile. Squeezing at zero dispersion does not possess this simple property. A gaussian pulse has different orientations of the phase of the squeezing ellipse across the pulse profile, and the pulse itself acquires a nonuniform phase. The noise reduction is compromised thereby. A square pulse would obviate this drawback, but is not realizable in practice because of unavoidable dispersion.

Positive dispersion reshapes the pulse as it propagates. One would expect, therefore, that one may manipulate the phase profiles by proper choice of pulse shape and GVD. This is indeed the case. We have made a detailed analysis of this process[5] and found that, under the appropriate conditions, the limits experienced by squeezing at zero dispersion can be overcome. Another advantage of using positive dispersion is that one may operate the system at wavelengths shorter than $1.3\mu m$ at which detectors of higher quantum efficiency are available.

Attempts have been made to verify the theory. Unfortunately, the laser at our disposal was not sufficiently low-noise to enable us to demonstrate significant squeezing.

Overcoming the Quantum Efficiency of Detectors

The ultimate limit on noise reduction is set by the quantum efficiency of the detectors. Perfect squeezing with a detector quantum efficiency of 90% can lead only to a 10dB reduction below shot noise. It is of interest, therefore, to look for ways of overcoming this limit.

We have investigated the possibility of phase sensitive amplification of the beams in the balanced detector before detection[6]. The preamplification is done via the same Kerr nonlinearity as employed in squeezing. In fact, it is well known that squeezing is the consequence of deamplification of the vacuum fluctuations of one phase with respect to the pump. The other phase is amplified. It is this amplification that can be employed in the twin beams of the balanced detector, after the beam splitter and before the detection. The parameter ranges for which this preamplification could be employed seem to be realizable

in practice.

Quantum Theory of Measurement

One of the remarkable features of squeezing experiments is that they involve nonclassical states, require a self-consistent quantum analysis, and are in general agreement with the quantum formalism developed for the analysis. This same formalism can serve as the basis for a theoretical treatment of quantum measurements. This topic has a long and controversial history. One reason for the controversy is the fact that it is difficult to analyze the measurement equipment quantum mechanically and, thus, the act of measurement is difficult to treat quantum mechanically. The von Neumann postulate of projection of the wave function into an eigenstate of the measurement apparatus is an attempt to avoid a detailed treatment of the act of measurement.

We have developed a detailed model for an optical measurement of photons, treating both the system to be measured and the measurement apparatus quantum mechanically. We have shown that the von Neumann postulate is consistent with results of a detailed treatment of the measurement process performed by a nonlinear Kerr interferometer, very similar to the type used in the squeezing experiments. The paper has been accepted for publication in *Phys. Rev. A*[7].

Awards:

Professor Haus received the President's 1995 National Medal of Science from President Clinton in the White House on October 18, 1995. The citation was: "For his fundamental and seminal research contributions to the fields of optoelectronics, noise and ultrafast optics, and for his service to the engineering profession through teaching."

PhD thesis:

L. Boivin, "Squeezing in Optical Fibers," February 1996.

References

1. S. Namiki, C. X. Yu, and H. A. Haus, "Observation of nearly quantum-limited timing jitter in an all-fiber ring laser," *J. Opt. Soc. Am. B*, submitted for publication.

2. F. X. Kärtner and L. Boivin, "Quantum noise of the fundamental soliton," *Phys. Rev. A*, 53 (1996), in press.

3. J. H. Shapiro and L. Boivin, "Raman noise limit for four-wave mixing," *Opt. Lett.* 18, pp. 925 (1994).

4. L. Boivin and H. A. Haus, "$\chi^{(3)}$-squeezed vacuum generation without a Sagnac interferometer," *Opt. Lett.* 21 (1996), in press.

5. L. Boivin, C. R. Doerr, K. Bergman, and H. A. Haus, "Quantum noise reduction using a Sagnac loop with positive dispersion," in *Quantum Communications and Measurement*, ed. V. P. Belavkin, O. Hirota, and R. L. Hudson (Plenum Press, New York, 1995), pp. 489-496.

6. F. X. Kärtner and H. A. Haus, "QND - measurement of twin beams," *J. Opt. Soc. Am. B*, submitted for publication.

7. H. A. Haus and F. X. Kärtner, "Optical quantum nondemolition measurements and the Copenhagen interpretation," *Phys. Rev. A*, submitted for publication.

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